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EVALUATION OF STRESS-RUPTURE PROPERTIES OF STAINLESS ALLOYS IN FLUIDIZED BED COMBUSTION ENVIRONMENTS

PHASE 1 REPORT

BY

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Any data presented, opinions, findings, conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of CANMET.

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SUMMARY

Phase 1 of the Contract was successfully completed according to the Statement of Work.

Stress-rupture tests were carried out on four alloys in a synthetic coal combustion atmosphere. The materials tested were Stainless Alloys 310, 347H and HK40 and Incoloy Alloy 800H. In general, rupture lives at 900°C were similar to those expected from tests in air reported in the literature. This was attributed to the gas having an oxidizing potential at 900°C. At 800°C and at low stress, rupture lives were generally shorter than would have been expected in air. This was attributed to the gas having a sulphidizing potential at 800°C. It was concluded that of the four alloys, Incoloy 800H was least suitable for service in a combustion atmosphere.

In preparation for Phase 2 a suitable simulated deposit attachment technique was developed and successfully tested.

1.0 INTRODUCTION

When coal is burned in a fluidized bed combustor, a large proportion of the sulphur in the fuel is trapped in the calcined limestone which, along with the resulting $CaSO_4$ makes up 95% of the bed. This capture of sulphur is most efficient in the temperature range 850 to 900°C but even in this temperature range, the concentration of SO_2 in the flue gas can reach 0.5%. Conditions vary from oxidizing (concentration of oxygen up to 5%) generally to reducing locally in the combustor. In addition, complex layers of compounds of oxygen, sulphur, calcium, iron, aluminum and silicon build up on the surfaces of metal components.

Boiler tubes in fluidized bed combustors operate at temperatures below the bed temperature but superheater tubes and hangers operate near bed temperature and are subjected to operating stresses and aggressive environments. The creep and stress-rupture properties of the stainless alloys which may be required in these high temperature applications are well known in air environments. However, in the aggressive environment of the fluidized bed combustor where progressive metal degradation is expected, data on mechanical properties are lacking. Consequently, an evaluation of the stress-rupture properties of these alloys in fluidized bed combustion atmospheres is required.

To fulfill this need Sherritt Gordon was engaged by the Federal Department of Supply and Services (DSS) to conduct stress-rupture tests. The effective commencement date was October 21, 1982. The contractual guidance for the project is provided by the Science Procurement Manager at DSS whilst the technical guidance comes from the Scientific Authority at CANMET (Canada Centre for Materials and Energy Technology). A three phase Statement of Work was provided with the contract and the date for conclusion of the third phase was set at February 28, 1985.

As outlined in the Statement of Work, the task of evaluating the stress-rupture properties of Stainless alloys types 310 and 347H, alloy HK40 and Incoloy 800H is divided into three phases. The objective of Phase 1 is to evaluate the stress-rupture properties of the specified alloys in simulated combustion gas using test temperatures of 800 and 900°C.

Phase 2 is similar to Phase 1 except that the alloys are to be in contact with an oxide/sulphate simulated deposit. Satisfactory completion of Phase 2 is dependent on the development of an application technique that will ensure that the oxide/sulphate phases remain in contact with the specimen during stress-rupture testing. Technique development work is to proceed during the time frame allotted for Phase 1.

Phase 3 repeats Phase 2 test procedures but two exotic alloys are to be substituted for the alloys tested in Phases 1 and 2.

This report deals specifically with the stress-rupture tests undertaken during Phase 1 in the period October 1982 to June 1983 and also describes the oxide/sulphate deposit application technique developed during the period.

2.0 EXPERIMENTAL

2.1 Materials

2.1.1 Alloys

The required stainless steel alloys types 310, 347H, HK40 and Incoloy 800H were obtained from commercial suppliers. Incoloy 800H and stainless alloys types 310 and 347H were purchased in the form of round bar of nominally 12.7 mm diameter. In the case of HK40, centrifugally cast pipe having a wall thickness of 12.7 mm was obtained. The alloys were purchased under the ASTM and UNS designations as shown below.

Alloy	Designation	
	ASTM	UNS
Stainless Steel Type 310	A249-80	S31000
Stainless Steel Type 347H	A479-80a	S34709
Alloy HK40	A608-79	J94224
Incoloy 800H	B408-77	N08810

Tables 1 and 2 show the chemical and room temperature physical properties of each alloy, together with comparative reference data. As indicated by the comparative data all alloys had chemical and physical properties within the limits expected.

2.1.2 Stress-Rupture Specimen Preparation

Machined specimens were prepared for stress-rupture testing according to ASTM designation E8-81 sections 6.1 and 6.4. Finished specimens conformed to the dimensional tolerances specified for small size specimens having nominal diameters of 6.25 mm and 25 mm gauge lengths, as shown in ASTM E8-81 Figure 8.

2.1.3 Synthetic Combustion Gas

Synthetic combustion gas having a nominal composition of 200 ppm carbon monoxide, 2000 ppm sulphur dioxide, 20% carbon dioxide and balance nitrogen was purchased from Matheson of Canada. Both the carbon monoxide and sulphur dioxide concentrations were guaranteed to be within ±10% of the nominal composition while the preparation tolerance for

Table 1 Chemical Analyses of Test Alloys

	Analyses (%)											
	Incoloy 800H			310			HK40			347H		
	Min	Max	Actual	Min	Max	Actual	Min	Max	Actual	Min	Max	Actual
Al	0.15	0.6	0.31	ns	ns	-	ns	ns	-	ns	ns	-
C	0.05	0.10	0.08	-	0.15	0.12	0.35	0.45	0.45	0.04	0.10	0.07
Cb+Ta	ns	ns	-	ns	ns	-	ns	ns	-	8xC	1.0	0.90
Cr	19.0	23.0	20.17	24.0	26.0	24.37	23.0	27.0	24.81	17.0	19.0	18.2
Cu		0.75	0.61	ns	ns	-	ns	ns	-	ns	ns	-
Mn		1.50	0.94	-	2.00	1.69	-	1.50	0.73	-	2.00	1.83
Mo	ns	ns	-	ns	ns	-	-	0.50	0.052	ns	ns	-
Ni	30.0	35.0	32.9	19.0	22.0	19.01	19.0	22.0	20.69	9.0	13.0	10.77
P	ns	ns	-	-	0.040	0.031	-	0.040	0.019	-	0.040	0.030
S		0.015	0.001	-	0.030	0.006	-	0.040	0.012	-	0.030	0.007
Si		1.0	0.60	-	0.75	0.66	0.50	2.00	1.11	-	1.00	0.48
Fe	39.5	ns	43.95	ns	ns	-	ns	ns	-	ns	ns	-
Ti	0.15	0.60	0.45	ns	ns	-	ns	ns	-	ns	ns	-
ASTM:	B-408-77			A249-80			A608-79			A479-80a		
UNS:	N08810			S31000			J94224			S34709		
Supplier	Inco Alloys Canada Ltd			Specialty Steels			Fahramet			Atlas Alloys		
Heat No:	(4) HH0898A M1989			40477			75016			A11330		

ns: Not specified

Table 2 Physical Properties of Test Alloys*

Alloy	Supplier	Heat No	Reference ASTM	Short Term Tensile			Hardness R_B	Grain Size ASTM
				YS(MPa)	UTS(MPa)	Elongation(%)		
310 Stainless	Specialty Steels	40477	A249-80	282(205)	642(515)	44(35)	80(90max)	8-9
347H	Atlas Alloys	A11330**	A479-80a	482(205)	662(515)	46(35)	99(ns)	9-10
HK40	Fahramet	75016	A608-79	ns***	ns			
800H	Inco Alloys Canada Ltd	HH0898A M1989	B408-77	179(170)	568(450)	56(30)	78(ns)	4.5

* Bracketed numbers represent minimum values, except as noted, from reference data

** Alloy heated to 1066°C min for sufficient time to dissolve carbides then quenched in water

*** As outlined in ASTM A608 Section 8 "tensile tests at room temperature are not recommended as acceptance criteria"

ns: Not specified

carbon dioxide and nitrogen was ±5% of nominal. The actual composition of the gas contained in each type 1R cylinder was certified by Matheson. The accuracy of the certification analyses was ±2% of the nominal composition.

2.2 Apparatus and Procedure

2.2.1 Apparatus

The stress-rupture evaluations for Phase 1 were conducted using stress-rupture machines and furnaces manufactured by Satec Inc. The equipment was designed so that stress-rupture testing could be conducted in accordance with ASTM designation E139-79. A schematic diagram of the apparatus is shown in Figure 1.

Each resistance heated furnace consisted of a sealed Inconel cylindrical retort equipped with a removable top and bottom. The material was later changed to Stainless Alloy 310. Viton O-rings and cup seals provided the required gas seal for both top, bottom and around the specimen pull rods (Inconel 713C) respectively. Cooling water which flowed through the removable top and bottom of each furnace protected the Viton seals. Synthetic combustion gas was supplied to each furnace through a common mild steel manifold to which four gas cylinders were connected. Gas from one of the cylinders connected to the manifold passed through a single pressure regulator which was used to maintain the gauge pressure at 140 kPa in the line which directed the gas to the bottom of each furnace via calibrated flowmeters. The flowmeters were used to control gas flow rates such that the gas velocity over the specimen surface was 100 mm/min. Each furnace gas inlet line was equipped with a valved gas sample point which could be used as a separate purge line when required. Exhaust gas exiting from the top of each furnace through Tygon tubing was scrubbed using a common caustic solution to remove sulphur dioxide and then vented to atmosphere.

Furnace temperature was maintained using an automatic temperature controller in conjunction with a calibrated type R Pt-Rh thermocouple positioned in the middle of the furnace near the resistance wire. Specimen temperature was continuously monitored using a strip chart recorder connected to a calibrated type R thermocouple located close to the centre of the specimen gauge length. This thermocouple was not attached to the specimen gauge length because during subsequent Phase 2 stress-rupture testing, the oxide/sulphate deposit would preclude thermocouple attachment to the gauge length.

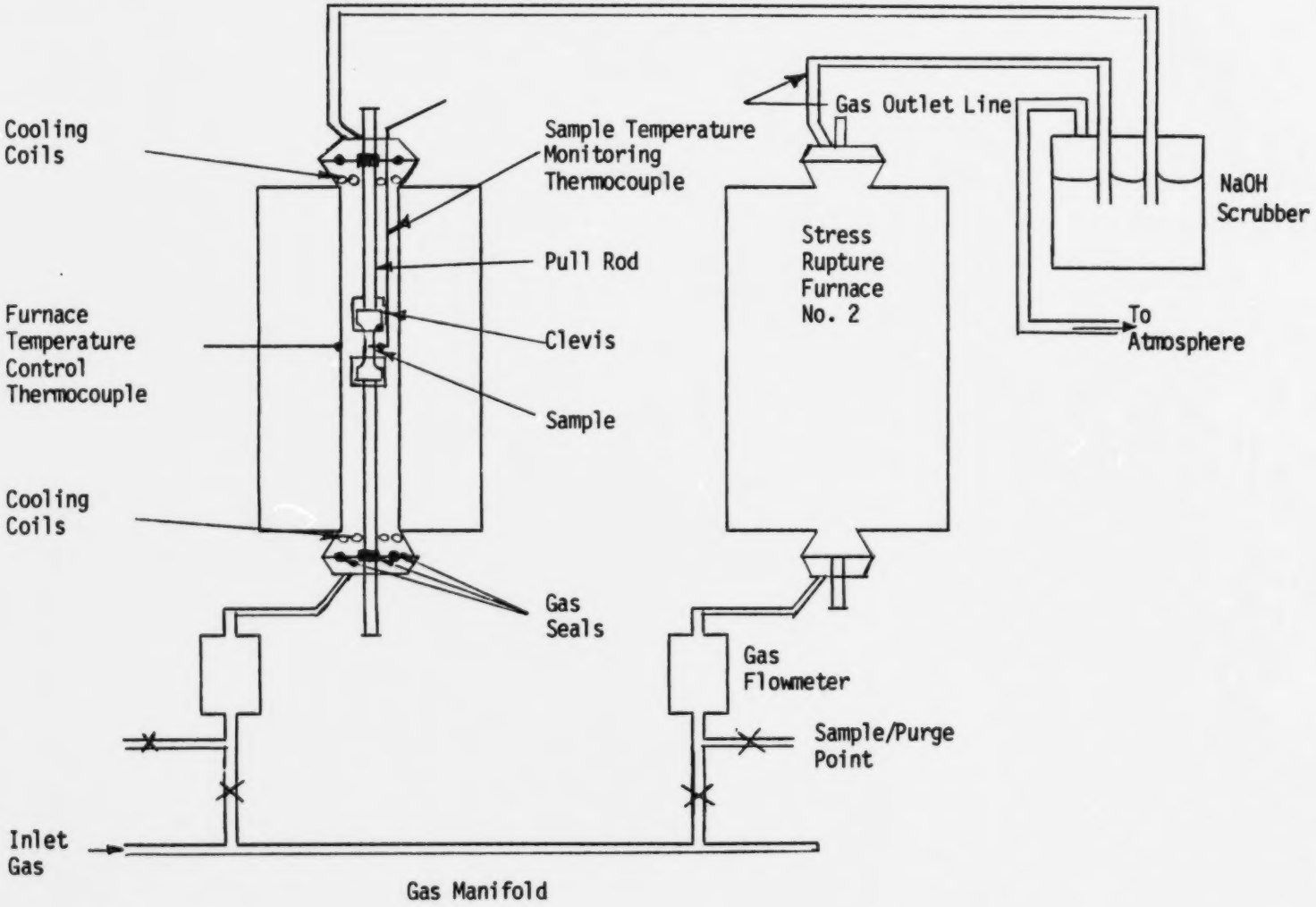

Figure 1 Schematic of Stress Rupture Testing Apparatus

2.2.2 Procedure

2.2.2.1 Stress-Rupture Testing

Prior to each stress-rupture test the uniformity of the hot zone,which would contain the 25 mm gauge length of the specimen, was verified. If required, the profile was adjusted so that the temperature was uniform within ±2°C over a 76 mm span. These profiles were determined using a furnace atmosphere of pure nitrogen (99.998% N_2) and gas flow rates similar to those which would be employed for actual stress-rupture testing.

After a test specimen was positioned in the furnace, pure nitrogen (99.998% N_2) was used to purge the furnace and the purge was continued until the specimen reached the desired test temperature.

The required load was then added to the load pan of the stress-rupture machine and synthetic combustion gas replaced the nitrogen in the furnace retort. During the tests, gas flows and specimen test temperature were routinely checked. In the case of specimen temperature, a calibrated digital potentiometer was used to verify the strip chart temperature record. It was observed that specimen temperature remained constant within ±3°C of the test temperature for the duration of each test. Analyses of gas samples, taken from the furnace inlet and exit synthetic combustion gas flows, were conducted at various times during the Phase 1 testing program. In all cases the composition of both gases was found to be the same. Additionally, in two tests the gas flow was reduced by 50% to each retort and during this period both the inlet and exit gas flows were sampled then analyzed. No difference in gas composition was found. The specimen temperature monitoring thermocouple was checked after various long term tests and in each instance no change in calibration was apparent.

The initial stress levels for each alloy were predicted from graphs which were based on Larson Miller Parameters (LMP)* computed with reference to stress-rupture test data in the literature. Although these graphs were based on stress-rupture tests conducted in air, they provided a logical starting point and also served as comparisons for Phase 1 test results. Figures 2 to 5 show the relation of LMP versus stress for the alloys while Figure 6 shows the corresponding predicted rupture life in air for stainless alloy type 310. Similar graphs were constructed for the other three alloys.

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* $LMP = T\,(20 + \log_{10} t)/556$ where T = Temperature (K) and t - time (h)

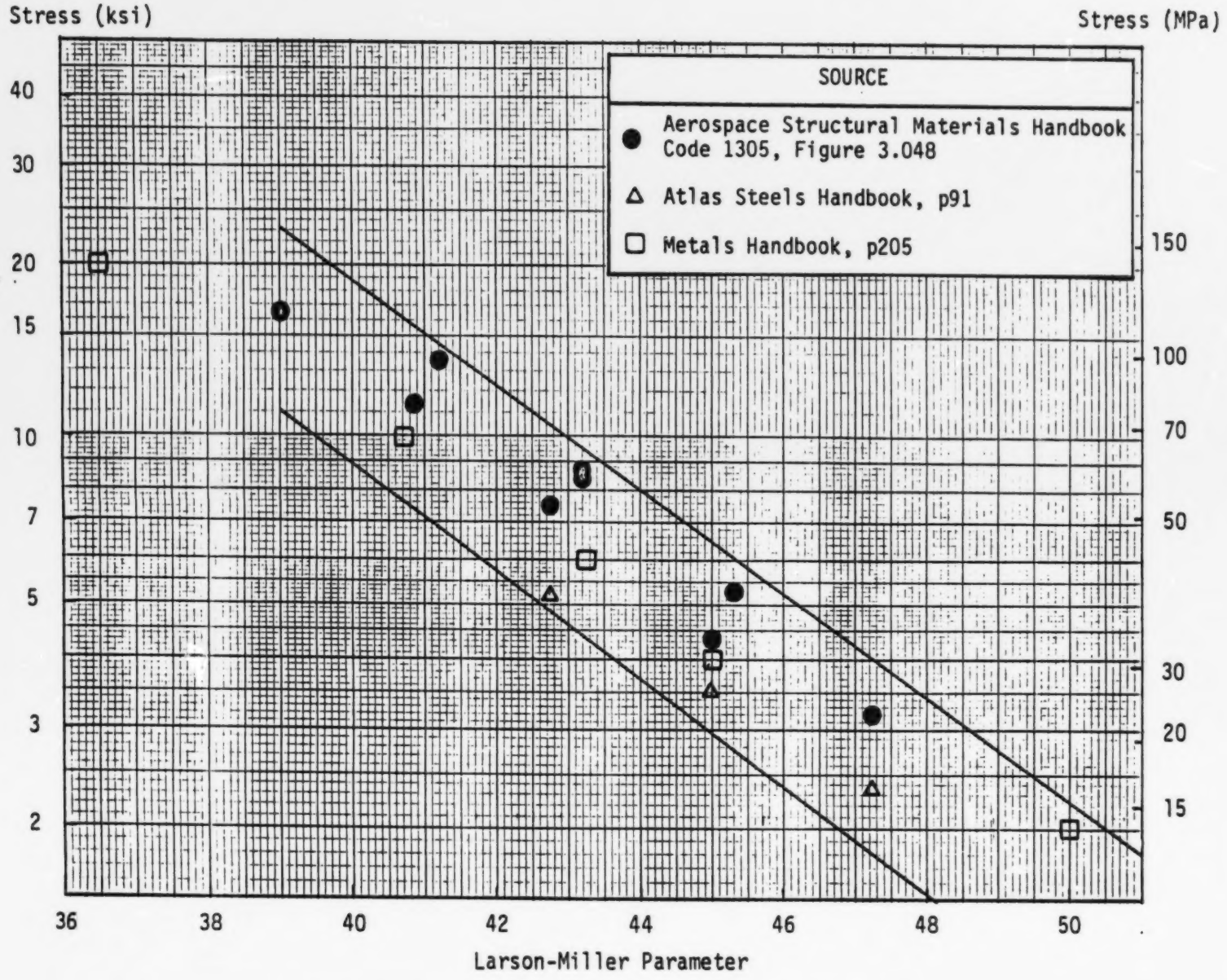


Figure 2 Larson Miller Parameter Versus Stress for Stainless Alloy 310

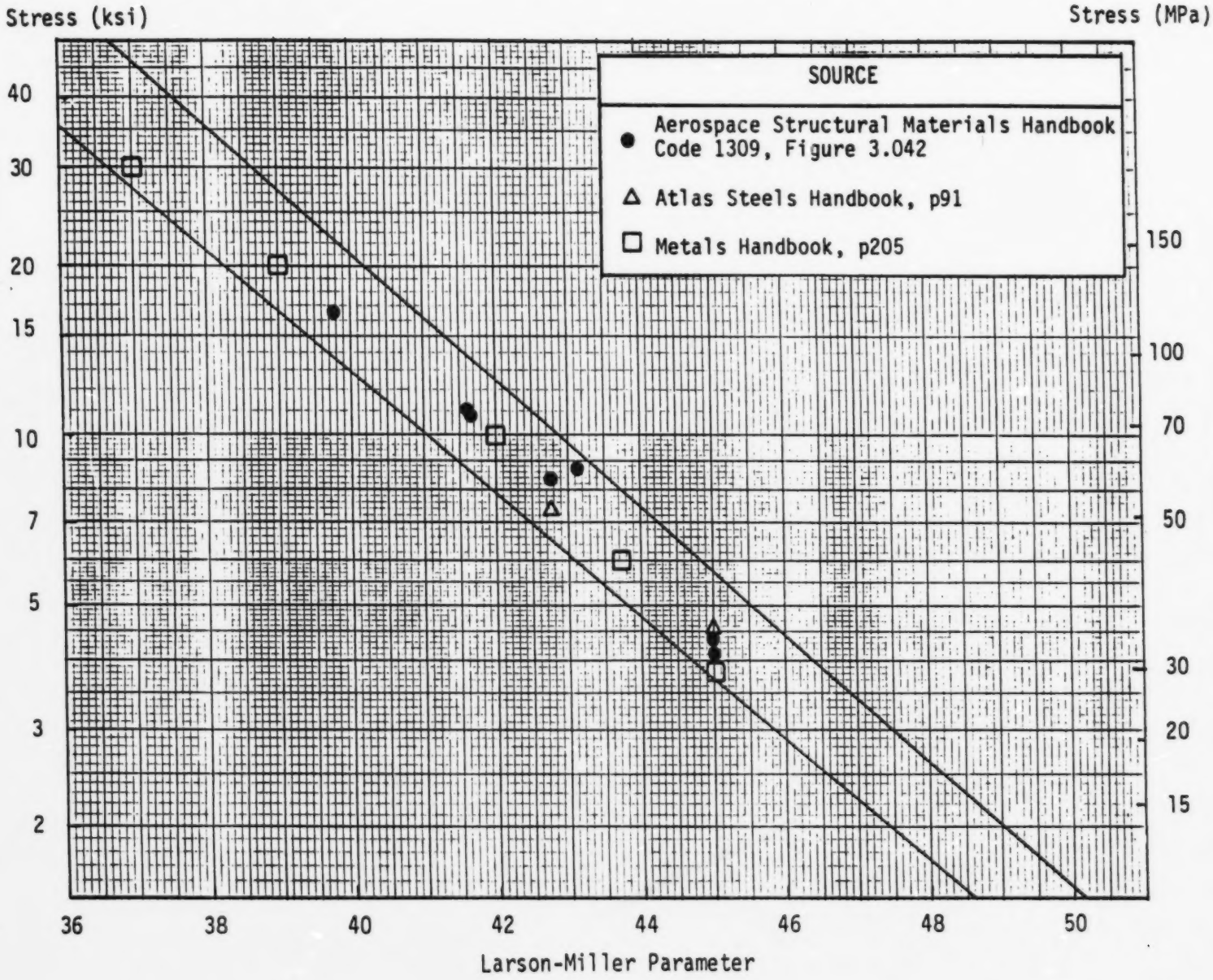


Figure 3 Larson Miller Parameter Versus Stress for Alloy 347

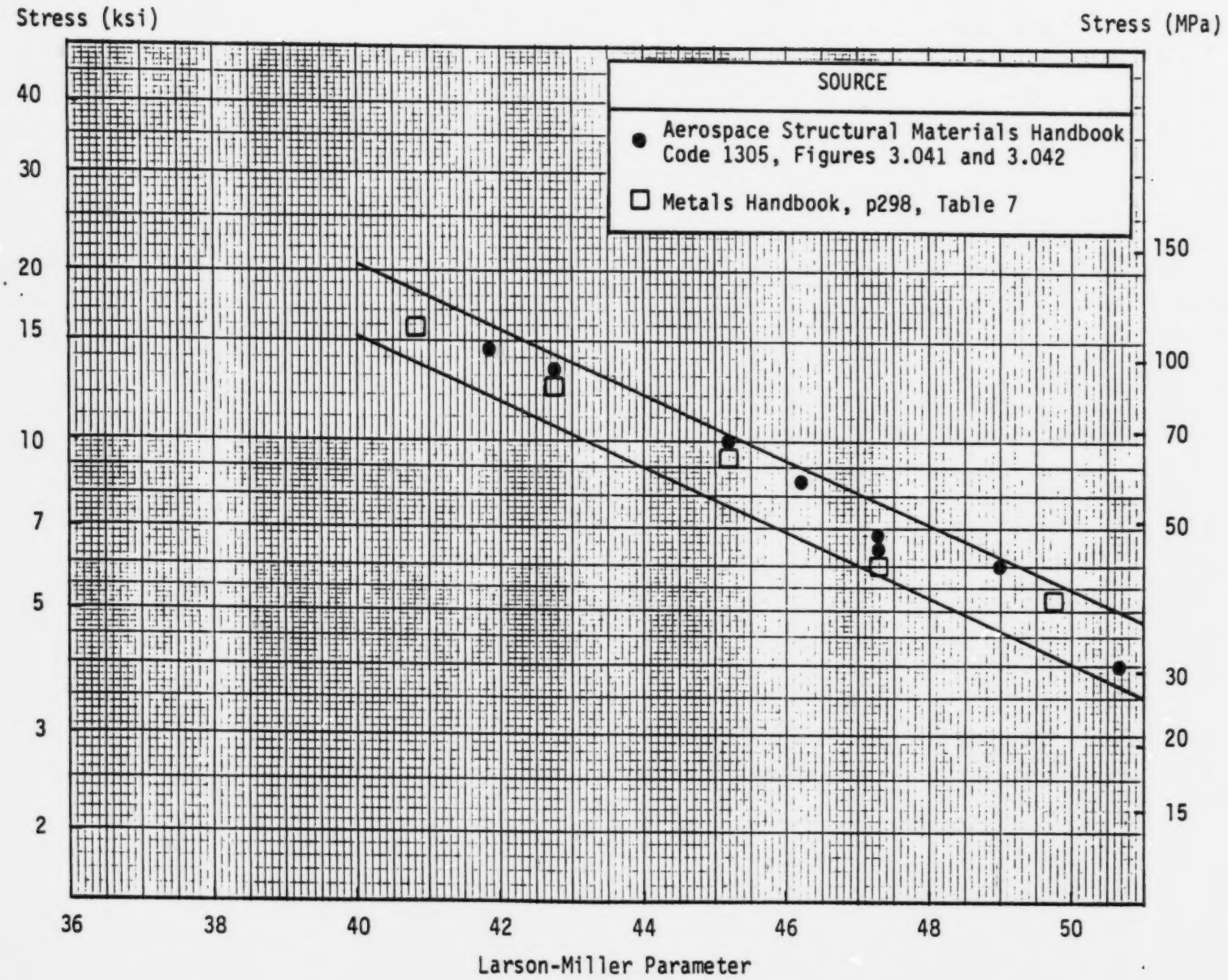


Figure 4 Larson Miller Parameter Versus Stress for Alloy HK40

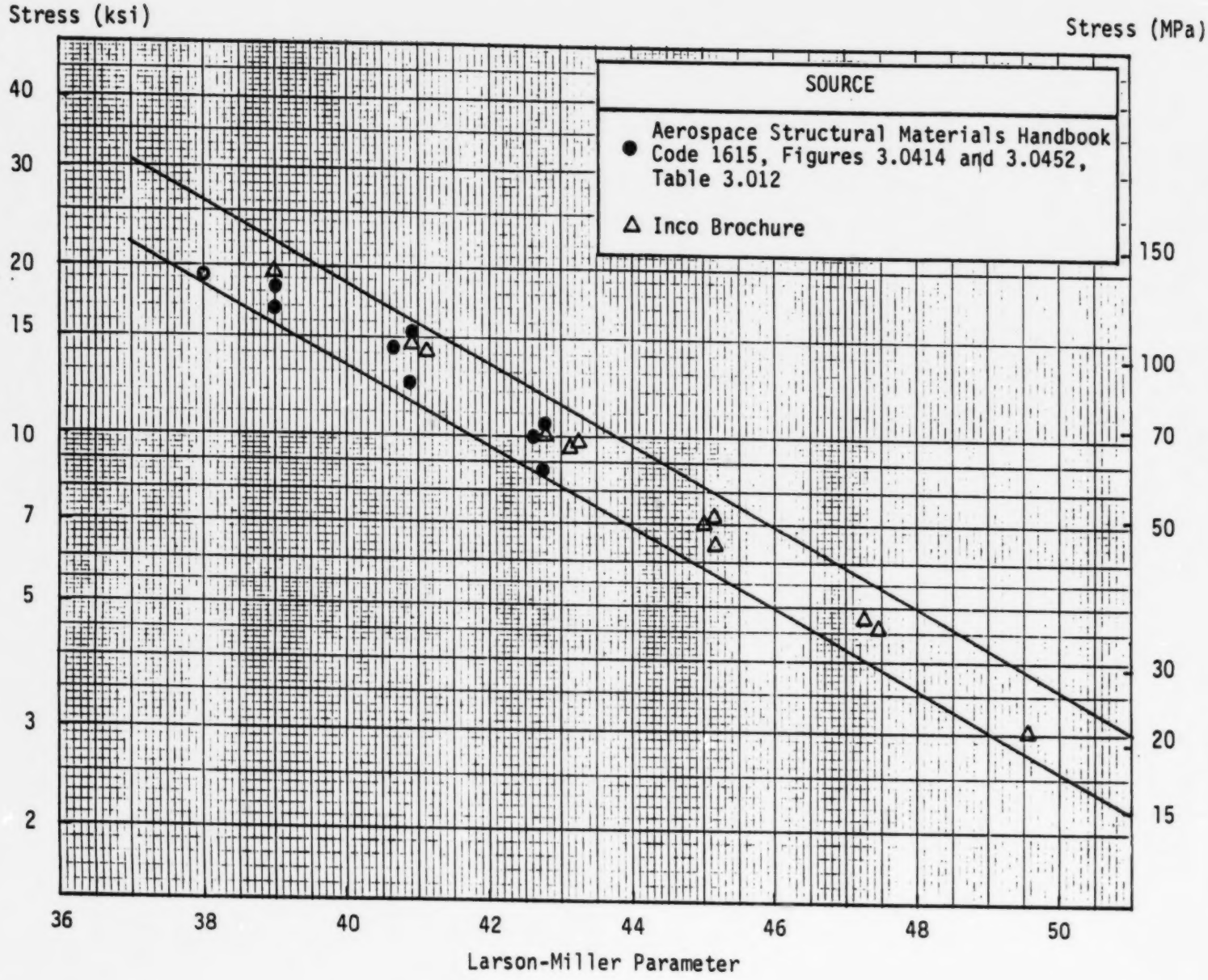


Figure 5 Larson Miller Parameter Versus Stress for Incoloy 800H

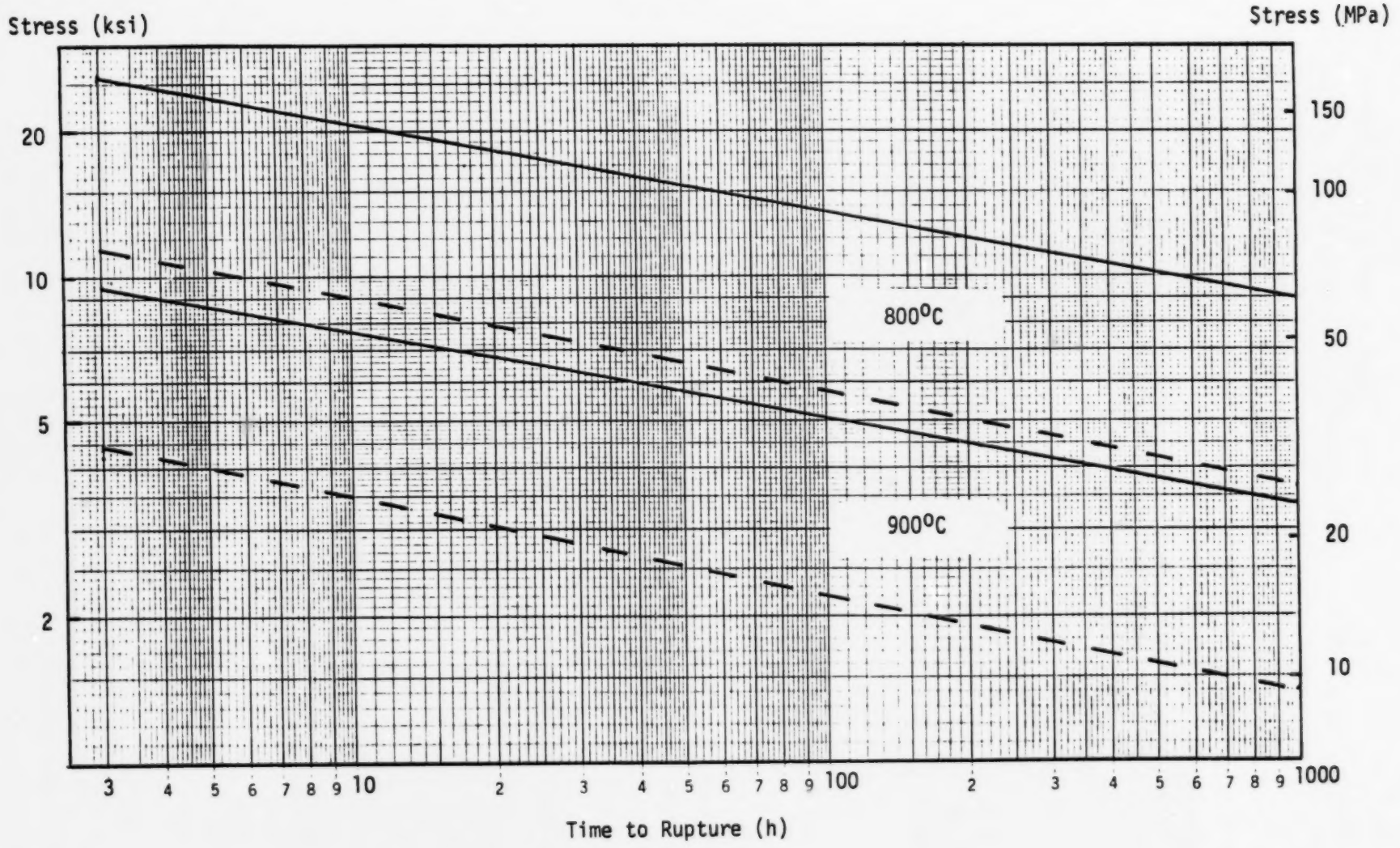


Figure 6 Predicted Rupture Life in Air for Alloy 310

In Figure 6, the two pairs of parallel lines bracket the minimum and maximum results expected for the test temperatures of 800 and 900°C and were based on data from Figure 2. It should be pointed out that the parallel lines indicate only in a general way the slope of data contained within them. Additional stress levels were chosen using the predicted rupture life graphs together with a least squares analysis of actual Phase 1 test results.

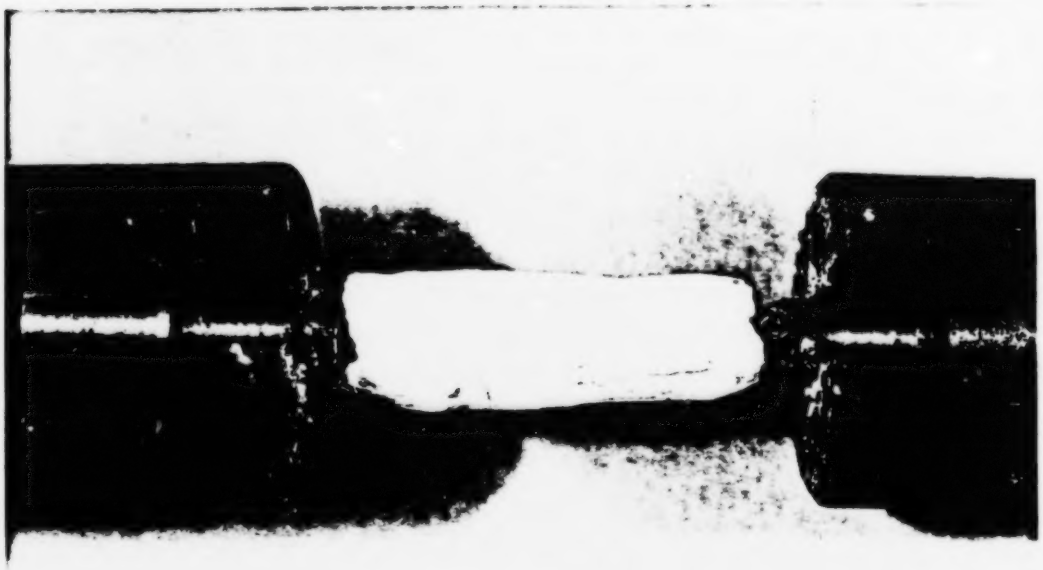
After rupture of the test specimen, electric power to the furnace was automatically switched off but synthetic combustion gas continued to flow through the retort during the furnace cooling period. Synthetic combustion gas flow was halted after the cooling period and the specimen was then removed from the retort. One of the two pieces of the ruptured specimen was set aside for subsequent transmittal to the Scientific Authority while the other piece was examined metallographically.

2.2.2.2 Technique for Application of Simulated Deposit to Test Specimens

Development of the technique for application of the deposit to test specimens was conducted concurrently with Phase 1 testing. The application technique would be required for Phase 2 stress-rupture tests. The simulated deposit consisted of CaO and $CaSO_4$ mixed in the ratio of 1:6. Initial trials involved mixing the two components with water to produce a slurry which was then applied to metal rods to build up the 3 mm thick deposit as specified by the Scientific Authority. After air drying the deposit, the slurry coated rods were heated for ~30 min at 900°C in pure N_2.

Inspection of the coated rods after heating showed that severe cracking of the dried slurry deposit had occurred and in some instances the simulated deposit had flaked off the rod.

Addition of the deposit to an aqueous 3% gelatin solution could be used to prepare a slurry which produced a deposit that remained intact and adhered to test rods after heat treatment (Figure 7A). (Note that the original signature report sent to the Scientific Authority has original photographs. Copies of the report have photocopied Figures.) However, it was found that the deposit failed to remain in intimate contact with test specimens during stress-rupture testing. Elongation of the test specimen during rupture testing caused reduction in cross sectional area and resulted in the specimen breaking away from the inelastic mortar-like deposit.



(a) Showing specimen with slurry coated simulated deposit

(b) Showing specimen with simulated deposit contained in Refrasil containment bag

Figure 7 Showing Simulated Deposit in Contact with Test Specimen

Since it was necessary that the deposit remain in contact with the specimen over the gauge length during stress-rupture testing it was decided to use a loose granular mixture of the simulated deposits packed in a bag which surrounded the test specimen (Figure 7B). The bag was fabricated using commercially available refrasil cloth (an amorphous refractory SiO_2 product). The technique was used in a stress-rupture test in which stainless alloy type 310 was subjected to a stress of 34.5 MPa in synthetic combustion gas at 900°C. The test was terminated after 60 h. After cooling and removing the sample from the retort it was found that the deposit containment bag was intact. From these tests it was concluded, after consultation with the Project Scientific Authority, that the latter procedure would be employed for subsequent Phase 2 stress-rupture tests.

3.0 RESULTS AND DISCUSSION

3.1 Stress-Rupture Data

3.1.1 Stainless Alloy 310

The stress-rupture results for alloy 310 tested in flowing synthetic combustion gas at 800 and 900°C are shown in Table 3 and Figure 8. With reference to Figure 8, it can be seen that these data fall within the limits expected for the rupture life of the alloy when tested in air. Least squares analyses of the 800°C data showed a steeper slope than the 900°C data.

3.1.2 Incoloy 800H

Data for Incoloy 800H are shown in Table 4 and Figure 9. Figure 9 shows that at high stress levels the rupture life in synthetic combustion gas was within the limits expected for the rupture life in air, but at lower stresses shorter rupture life was evident, with the 800°C result showing the largest deviation. As with the 310 alloy, the curve fit to the 800°C rupture results had the steeper slope.

3.1.3 Alloy HK40

The stress-rupture data for HK40, shown in Table 5 and Figure 10 were similar to that obtained for Incoloy 800H in that only the lower stress levels at each temperature resulted in a rupture life shorter than that expected in air.

3.1.4 Alloy 347H

Table 6 and Figure 11 show the stress-rupture results for alloy 347H. Like alloy 310, the data compared reasonably well with the expected rupture life in air although at 800°C, high stress levels yielded a rupture life which was somewhat longer. The maximum-minimum bands used in the Figure however refer to alloy 347 test data not 347H which may account for the anomaly. Again, the slope of the line fit to the 800°C data was steeper compared to the computer fit curve for the 900°C results.

Table 3 Stress Rupture Data for Stainless Alloy 310 Tested in Synthetic Combustion Gas

Stress (MPa)	Time to Rupture (h)	Elongation (%)
Test Temperature 800°C		
110.4	3.2	66
88.3	12.4	40
74.5	24.7	33
58.7	77.7	28
38.0	511.2	21
Test Temperature 900°C		
60.7	3.4	nd
48.3	11.9	40
34.5	50.2	37
27.6	173.1	33
20.7	833.7	32

nd: Not determined

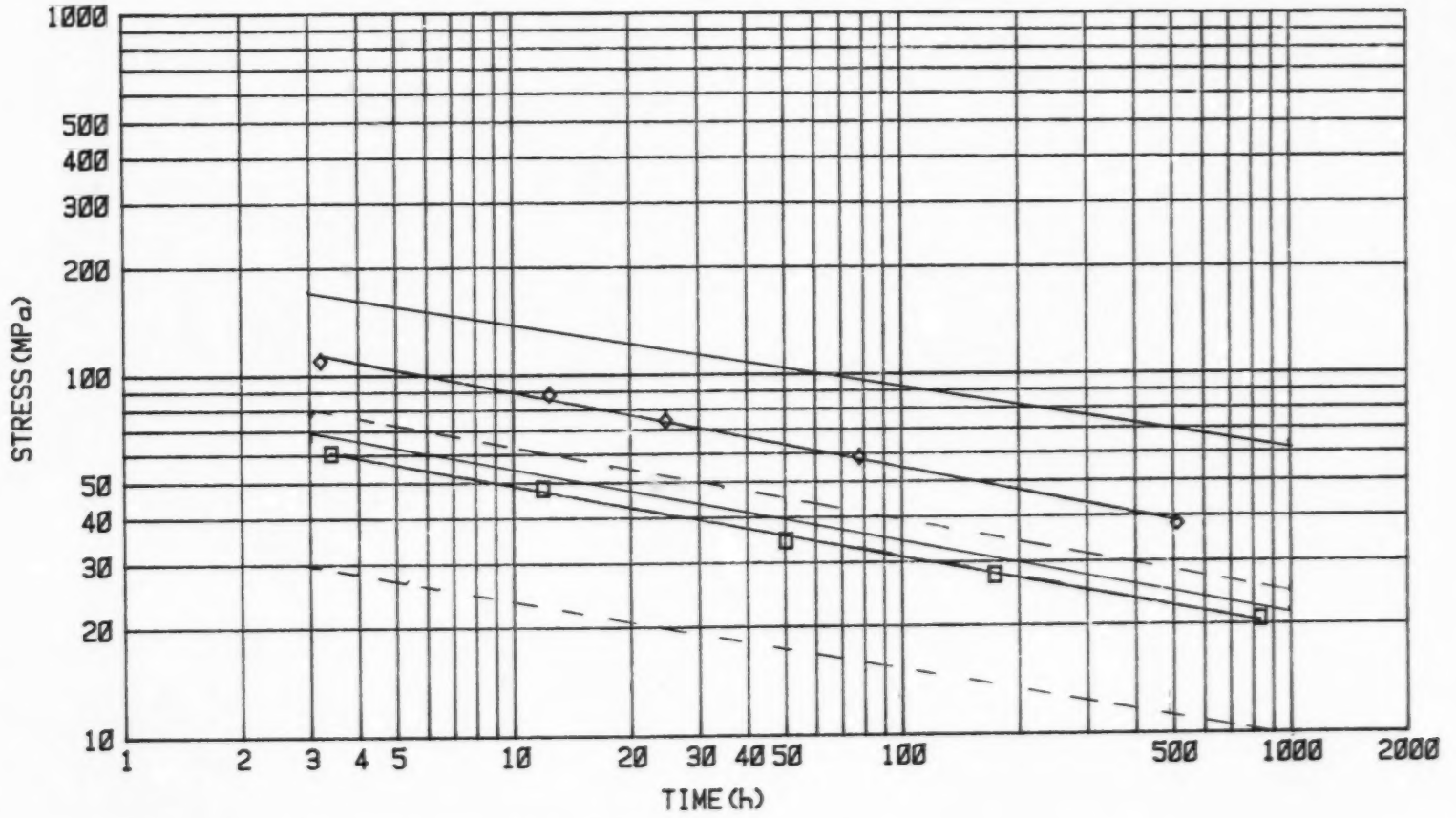


FIGURE 8: S/R TESTS FOR ALLOY 310
IN SYNTHETIC COMBUSTION GAS

◇ 800 C

□ 900 C

Table 4 Stress Rupture Data for Incoloy 800H Tested in Synthetic Combustion Gas

Stress (MPa)	Life to Rupture (h)	Elongation (%)
Test Temperature 800°C		
124.2	2.6	58
103.5	11.1	Heavy Corrosion
82.8	25.1	Heavy Corrosion
70.4	68.7	Heavy Corrosion
44.5	573.7	Heavy Corrosion
Test Temperature 900°C		
58.7	4.5	39
48.3	13.8	25
36.6	65.8	22
30.4	291.0*	Gauge Marks Obscured
26.2	240.8	nd
22.4	1004.9	32

* Synthetic combustion gas ran out after 265 h; N_2 used for balance of test

nd: Not determined

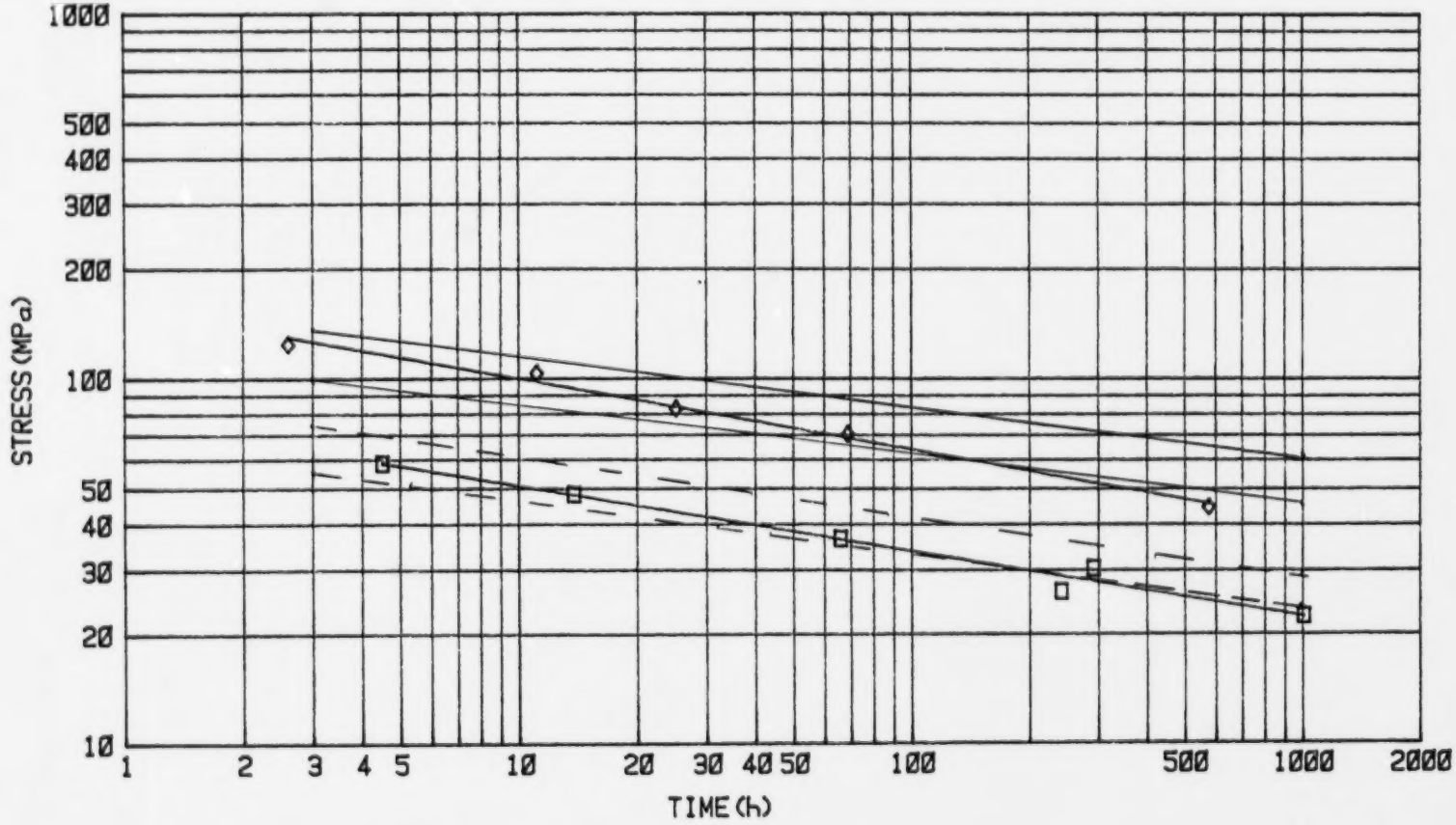


FIGURE 9: S/R TESTS FOR INCOLOY 800H
IN SYNTHETIC COMBUSTION GAS

◇ 800 C

□ 900 C

Table 5 Stress Rupture Data for Alloy HK40 Tested in Synthetic Combustion Gas

Stress (MPa)	Time to Rupture (h)	Elongation (%)
Test Temperature 800°C		
151.8	4.5	20
131.1	13.1	12
98.7	68.5	5
86.3	73.5	nd
86.3	91.1	6
55.2	492.3*	nd
Test Temperature 900°C		
89.7	5.9	14
75.9	15.7	Gauge Marks Obscured
56.6	59.5	4
44.9	95.3	2
31.7	957.3**	5

* Power failure, sample broke on cooling

** Gas was at half flow for 168 h because of a shortage in supply

nd: Not determined

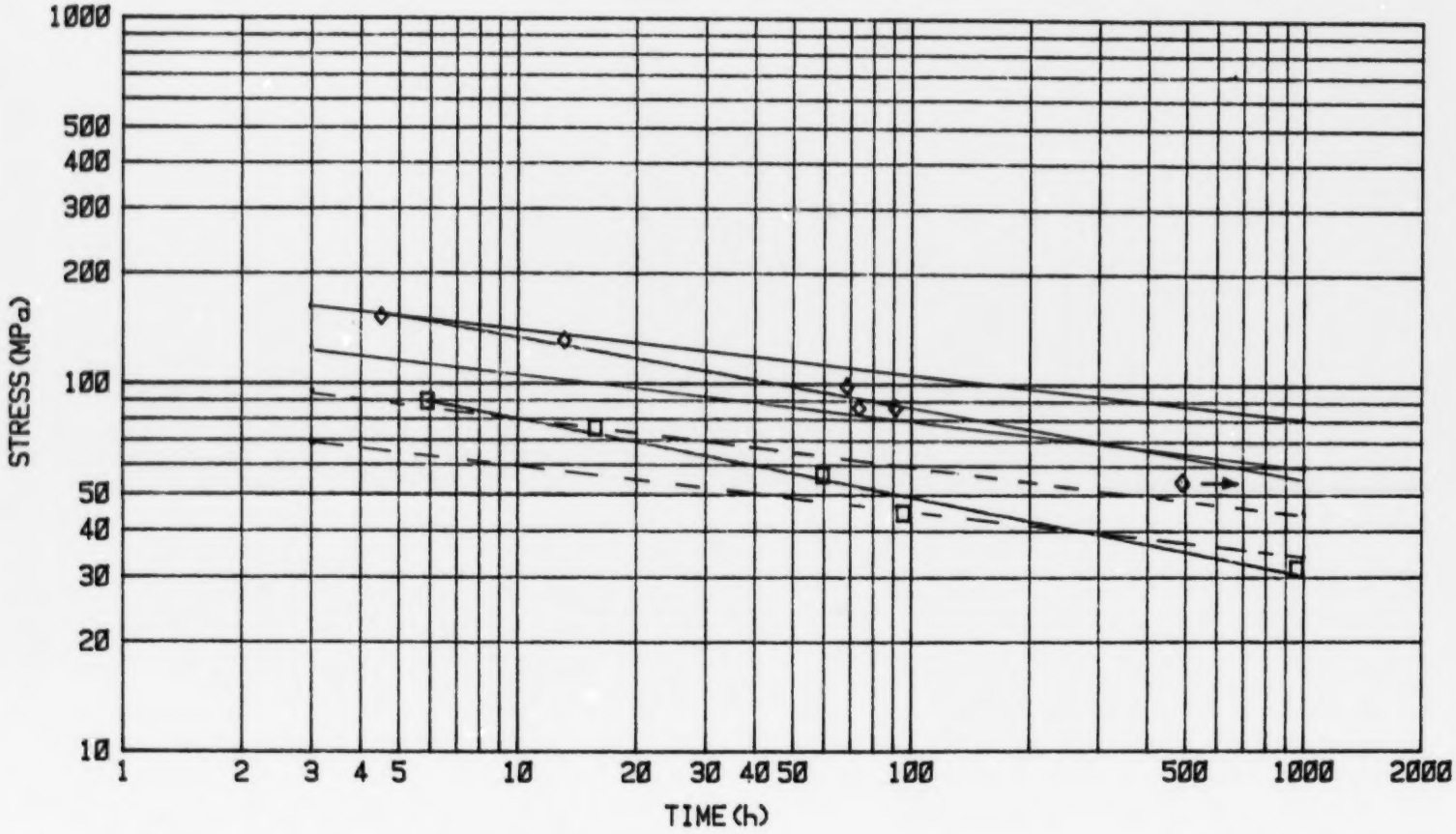


FIGURE 10: S/R TESTS FOR ALLOY HK40
IN SYNTHETIC COMBUSTION GAS

◇ 800 C

□ 900 C

Table 6 Stress-Rupture Data for Alloy 347H Tested in Synthetic Combustion Gas

Stress (MPa)	Time to Rupture (h)	Elongation (%)
Test Temperature 800°C		
189.8	0.3	40
158.7	7.0	34
131.1	16.7	43
100.0	40.0	60
75.9	76.5	60
35.9	1352.7*	95
Test Temperature 900°C		
65.6	2.6	72
44.2	14.5	80
32.4	44.4	113
24.8	107.0	88
14.5	640.9	70

* Gas was at half flow for 168 h because of a shortage in supply

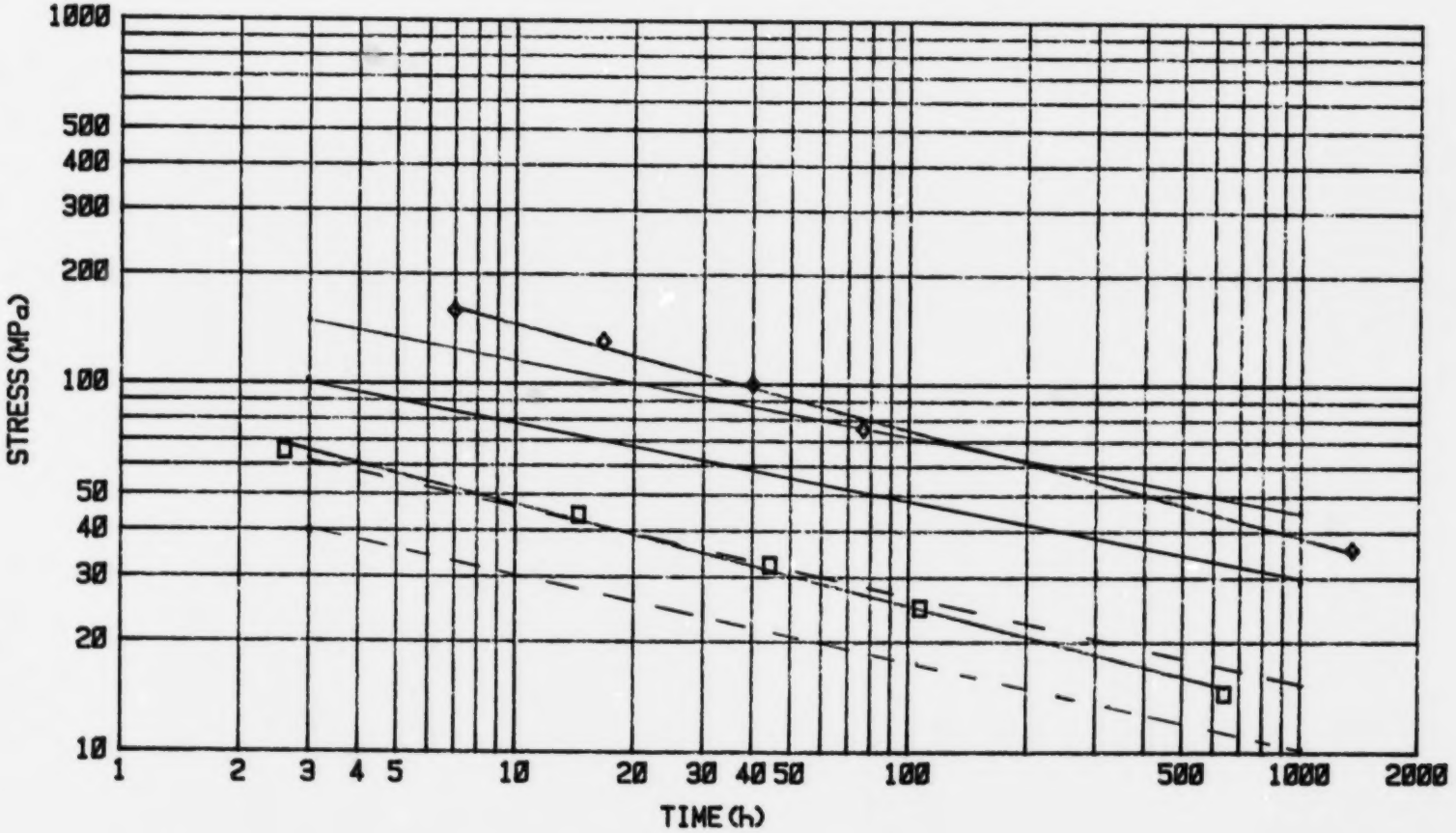


FIGURE 11: S/R TESTS FOR ALLOY 347H
IN SYNTHETIC COMBUSTION GAS

◇ 800 C

□ 900 C

3.2 Metallography

3.2.1 As Received Alloys

Micrographs of the starting alloys are shown in Figure 12. Alloy 800H appeared to have the largest grain size while 347H had the smallest. In the literature the microstructure of HK40 is described as being characterized by the presence of massive carbides as scattered islands or networks, and as shown in Figure 12, the microstructure of the as received HK40 fit this description very well.

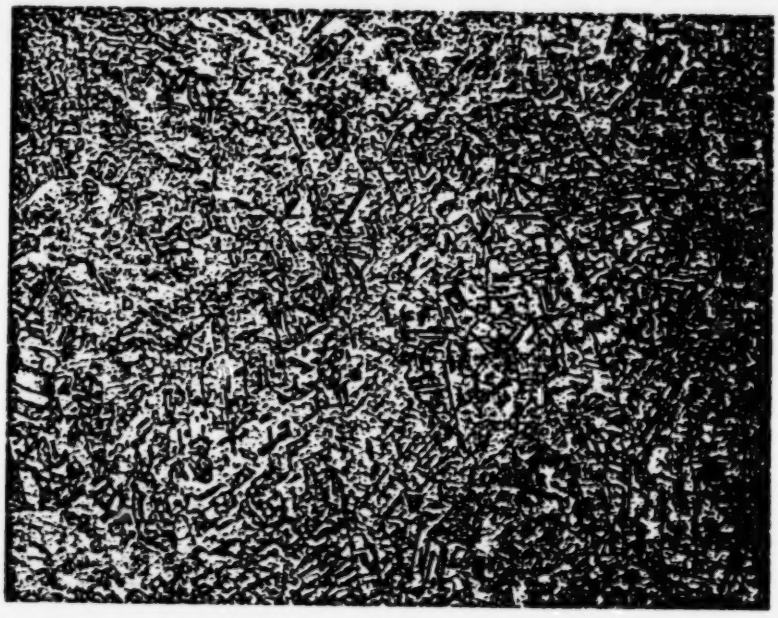
3.2.2 Ruptured Specimens

In Figures 13 to 16, photographs show the appearance of the test specimens after stress-rupture testing. These photographs show that the Incoloy 800H appeared to be the most corroded. Alloy 347H had more surface attack at 900°C than at 800°C and HK40 and 310 showed the least attack. Alloy 347H and alloy 310 both appeared to have a darker discoloration after testing at 900°C compared to 800°C. With respect to mode of fracture, HK40 showed the least elongation at both temperatures while 347H showed greater elongation at 900°C compared to 800°C.

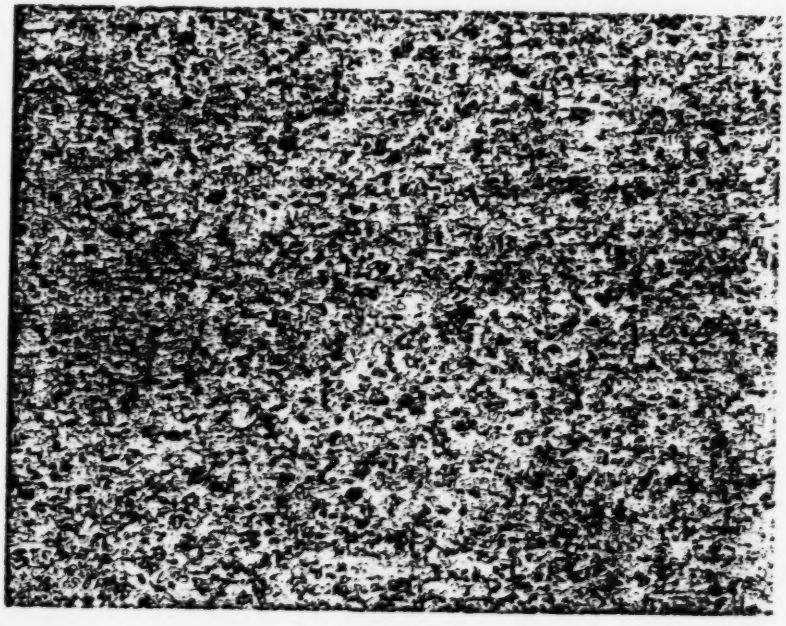
3.2.3 Metallographic Examination of Ruptured Specimens

Detailed metallographic examination of alloy 800H showed that more sulphidation occurred at 800°C than at 900°C. A good comparative example is shown in Figure 17. Lower stress levels at both temperatures resulted in less surface attack. Figure 18 shows the cross section near the fracture of the specimen tested using a stress of 44 MPa at 800°C. Time to rupture was ~570 h. Also shown in the Figure is an example of the sulphidation which was observed. Note that sulphidation appeared to be following a stress crack from the surface into the matrix. Comparative micrographs of a specimen tested at 900°C with a stress of ~29 MPa are shown in Figure 19. Time to rupture was ~1000 h. The typical intergranular mechanical nature of the failure can be seen in the higher magnification micrograph.

Metallographic examination of HK40, 310 and 347H showed that less sulphidation had occurred at both temperatures in these alloys compared to 800H. The trend of more alloy surface attack at high stress levels as observed in 800H was not nearly as marked in these alloys. Examples of the microstructures and surface attack observed in the three alloys

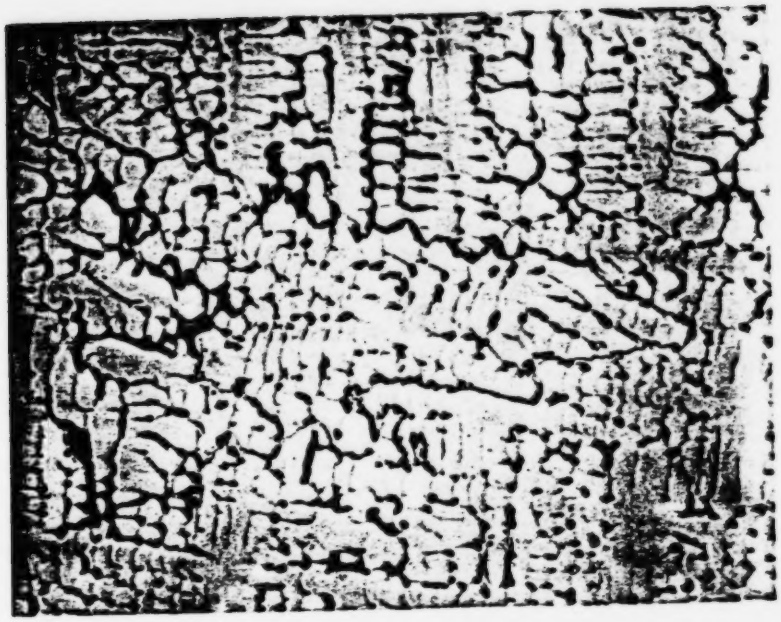


(a) Alloy 310: Etched in $HNO_3/HAc/HCl/H_2O$ Mixture

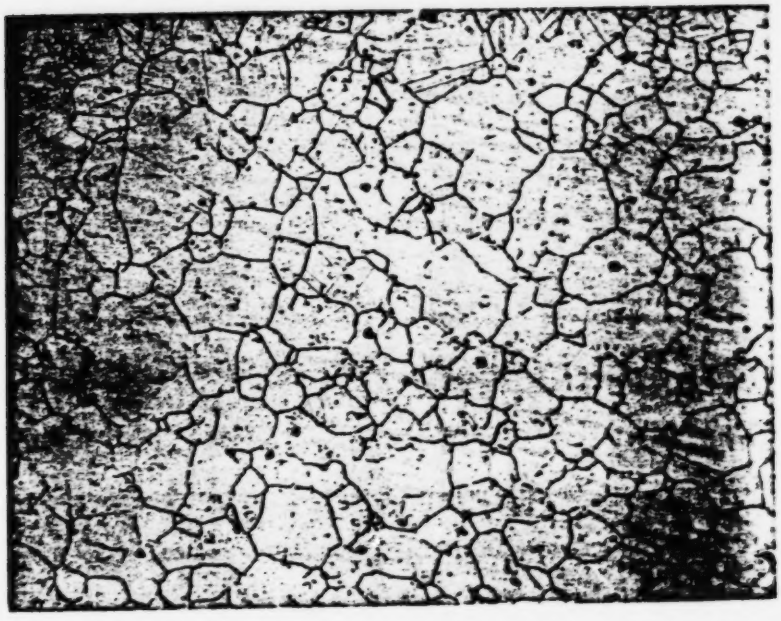


(b) Alloy 347H: Etched in $HNO_3/HAc/HCl/H_2O$ Mixture

Figure 12 Photomicrographs Showing the Microstructures of the Alloys Prior to Stress Rupture Testing (X100)

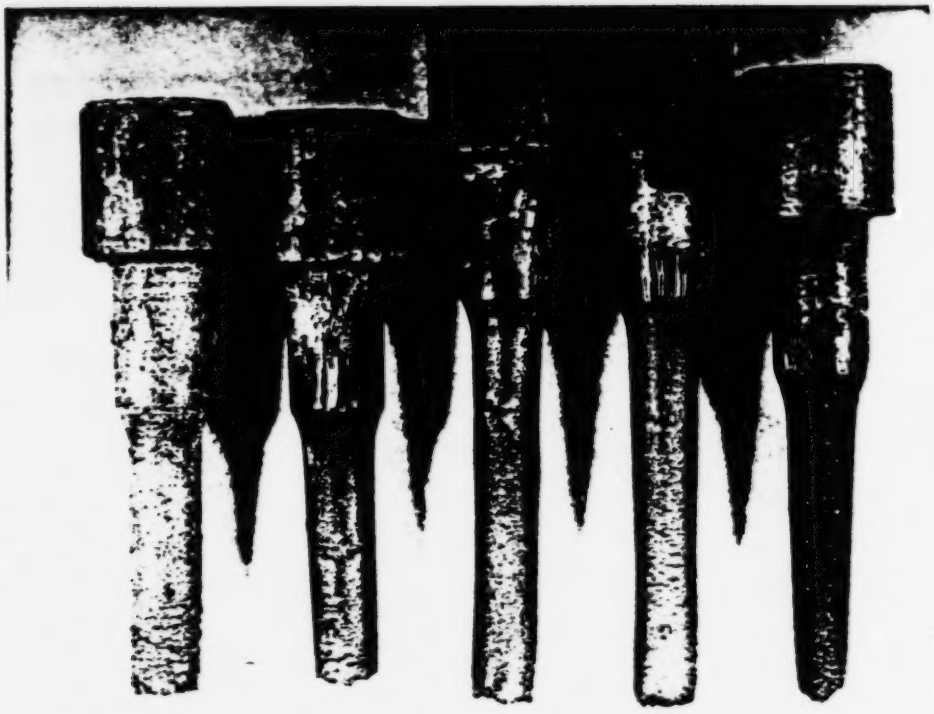


(c) Alloy HK40: Etched in HNO_3/HAc/HCl/H_2O Mixture



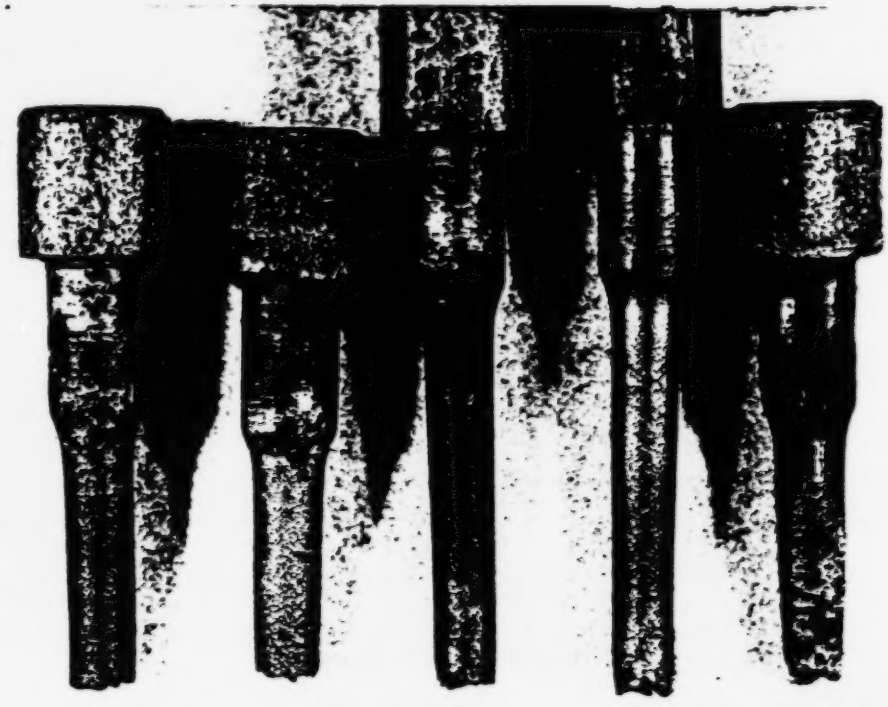
(d) Incoloy 800H: Etched in HNO_3/HAc/HCl/H_2O Mixture

Figure 12 Continued



800°C
Test
Temperature

Low Stress High



900°C
Test
Temperature

Low Stress High

Figure 13 Showing Appearance of 310 After Stress Rupture Testing in Synthetic Combustion Gas at 800 and 900°C

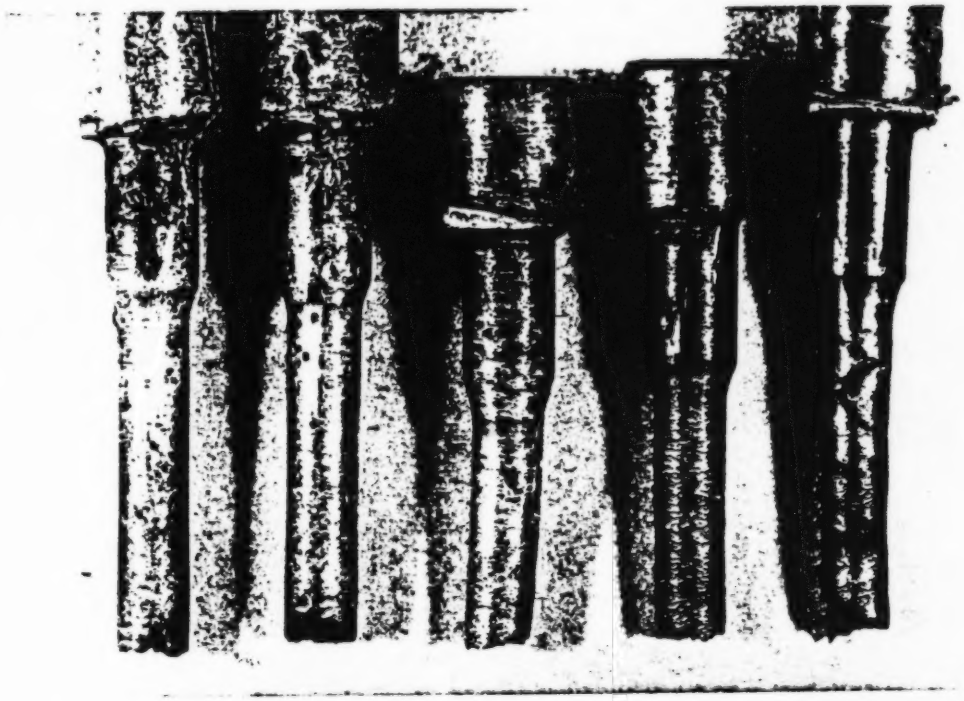
800°C
Test
Temperature

Low Stress High

900°C
Test
Temperature

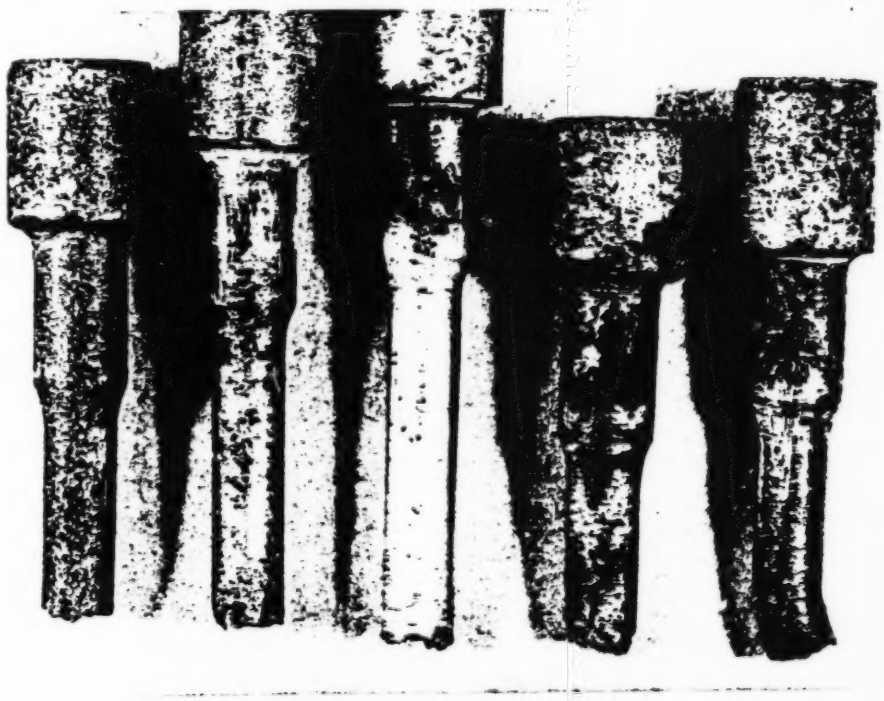
Low Stress High

Figure 14 Showing Appearance of 800H After Stress Rupture Testing in Synthetic Combustion Gas at 800 and 900°C



800°C
Test
Temperature

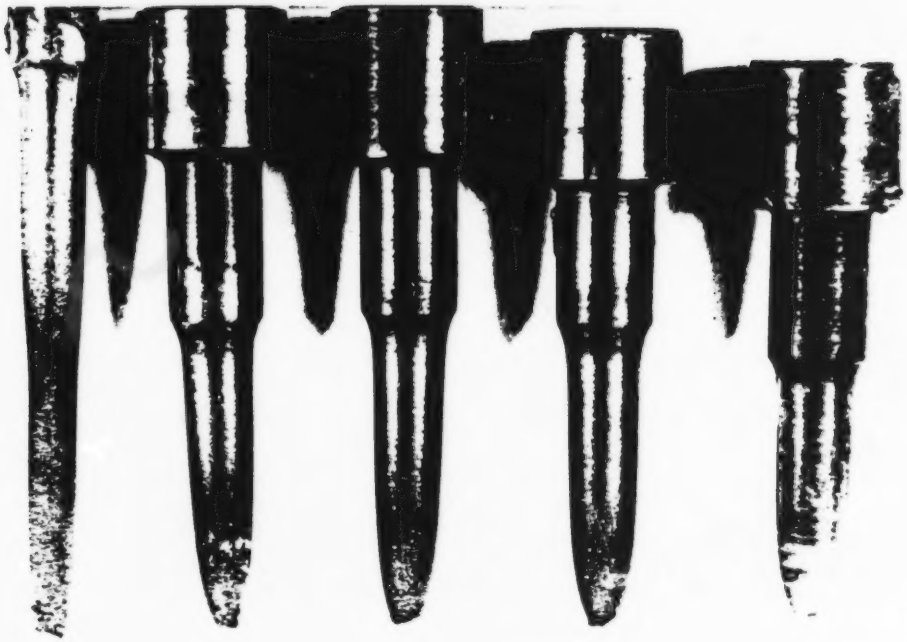
Low Stress High



900°C
Test
Temperature

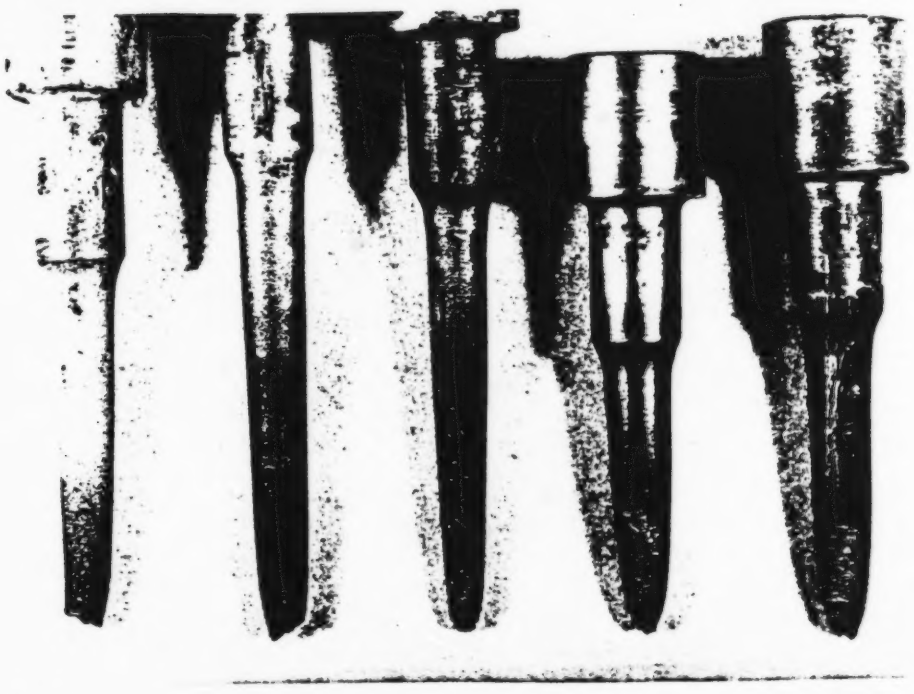
Low Stress High

Figure 15 Showing Appearance of HK40 After Stress Rupture Testing in Synthetic Combustion Gas at 800 and 900°C



800°C
Test
Temperature

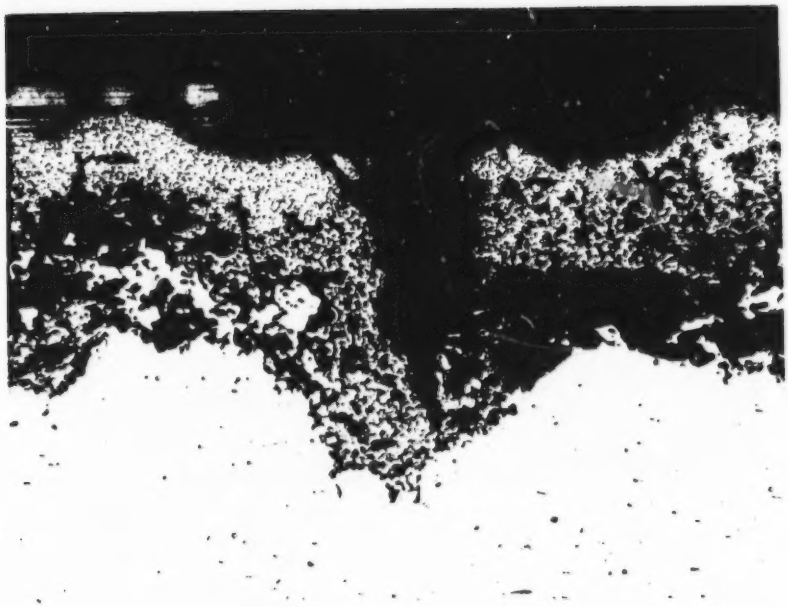
Low Stress High



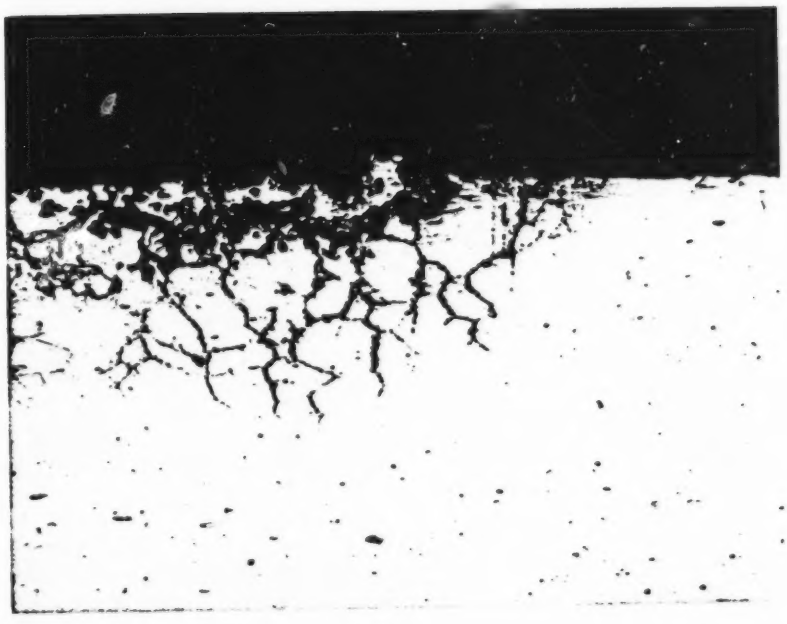
900°C
Test
Temperature

Low Stress High

Figure 16 Showing Appearance of 347H After Stress Rupture Testing in Synthetic Combustion Gas at 800 and 900°C

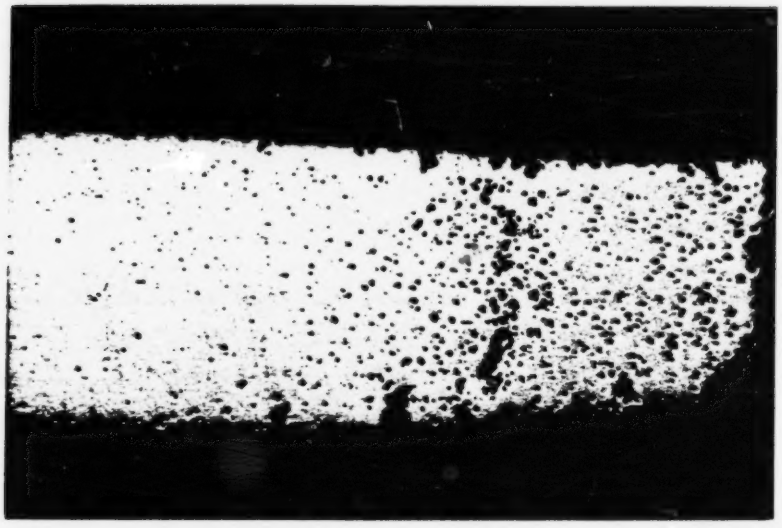


800°C



900°C

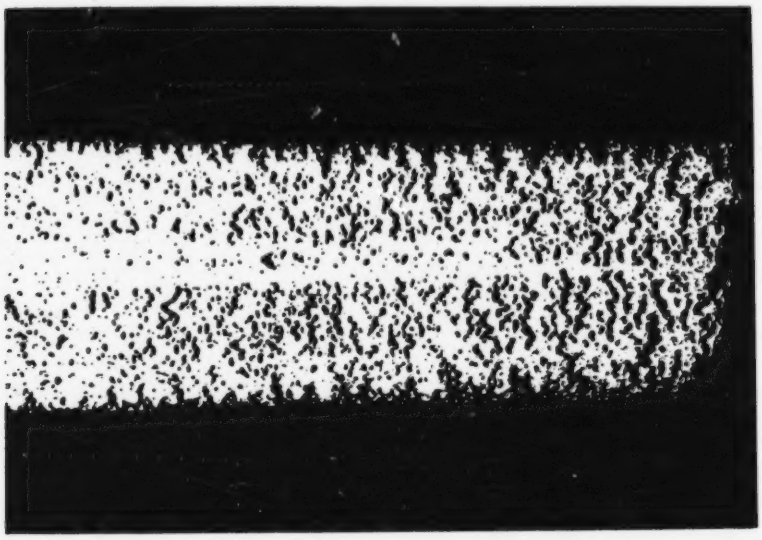
Figure 17 Photomicrographs Showing Sulphidation in Incoloy 800H Tested at 800 and 900°C Using High Stress in Synthetic Combustion Gas (X100)



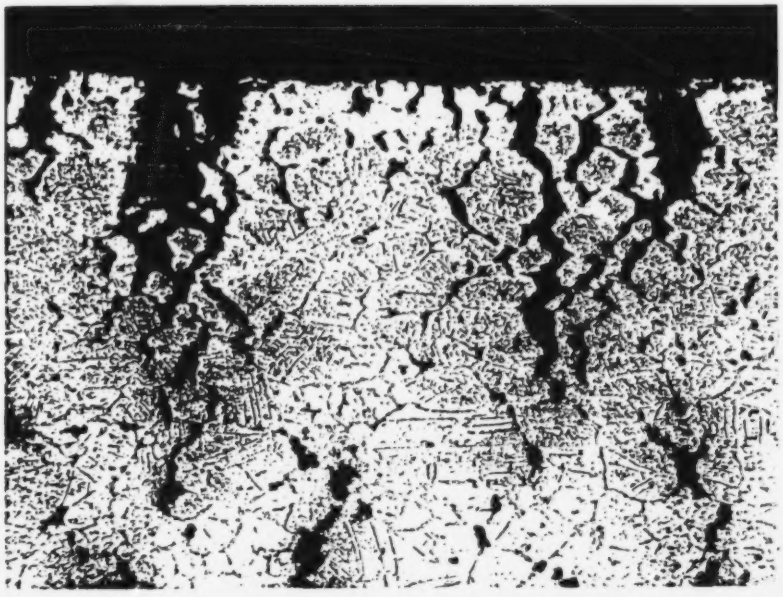
(X10)

(X100)

Figure 18 Photomicrographs of Incoloy 800H After Testing at 800°C Using a Low Stress in Synthetic Combustion Gas



(X10)



(X100)

Figure 19 Photomicrographs of Incoloy 800H After Testing at 900^{o}C Using a Low Stress in Synthetic Combustion Gas

after fracture at high stress levels are shown in Figure 20. The relative degree of surface attack and inward penetration appeared to correlate with degree of mechanical deformation expressed as elongation. In samples which were tested at low stress levels and long times, relatively little corrosion was observed in areas away from the deformation sites. The mechanical deformation and corrosion observed in 310, 347H and HK40 tested under conditions of low stress are shown in Figure 21.

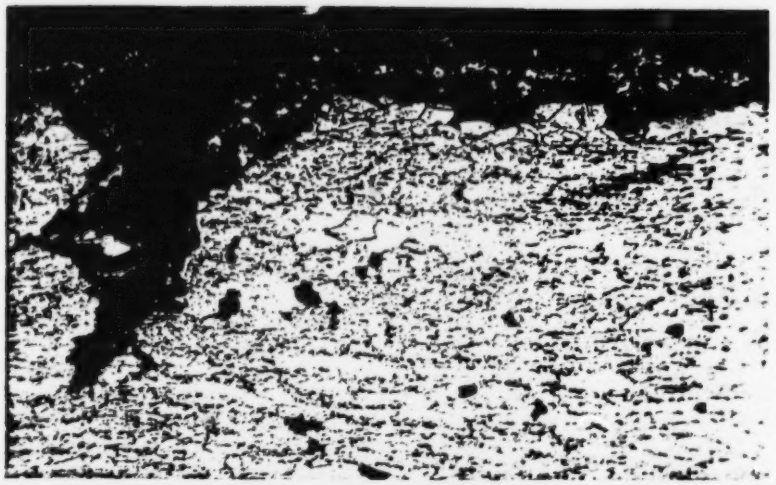
The stress-rupture data, together with the metallographic examination, suggest that high stress may have promoted hot corrosion by the destruction of a protective oxide coating. At low stress, corrosion also appears to correlate with degree of mechanical deformation. However under the conditions of stress-rupture testing in Phase 1, mode of specimen failure appears to be due to mechanical means which tend to override any major effect of corrosion and thus the rupture lives of the alloys do not depart markedly from the expected rupture lives in air.

The greater comparative corrosive attack of 800H was likely due to the high nickel content of the alloy. Similar behavior was observed in the Inconel 713 (high Ni) retort liners, pull rods and clevises used in Phase 1 testing. Increased life for the pull rods and clevises has been achieved by oxidizing these at 1000°C in air prior to use in the synthetic combustion gas.

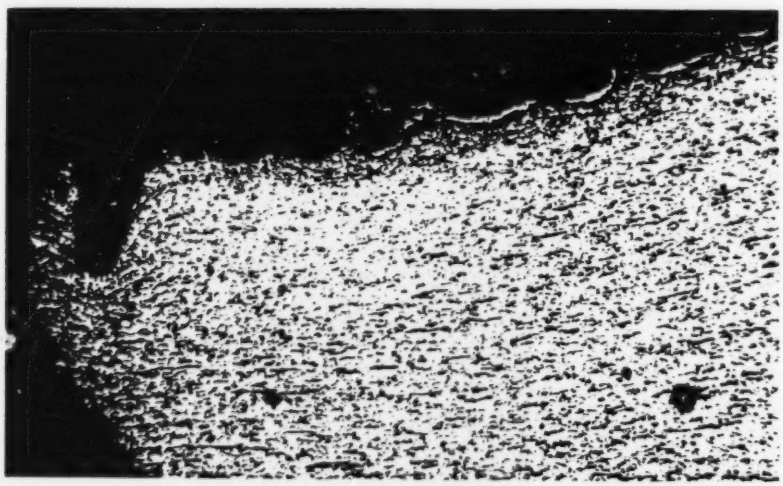
In general, the steeper slope of the curves fit to the 800°C test results compared to 900°C data likely reflected the known higher sulphur potential of the combustion gas at 800°C. At 900°C, the gas has an oxidizing potential (promoting formation of a protective oxide coating) which may account for the similarity in the test results when compared to the results expected when testing in air. Collectively these data suggested that 310, 347H and HK40 would appear to be best choices for service in the synthetic combustion gas.

3.2.4 Effect of Simulated Deposit

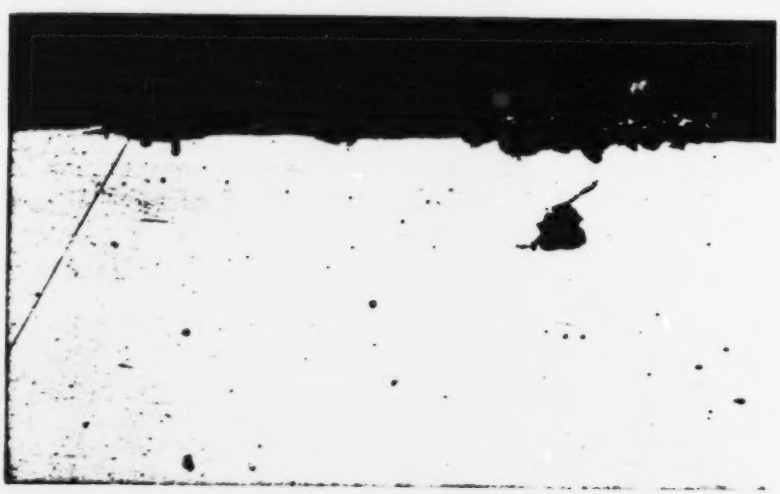
During development of the technique for application of the CaO and $CaSO_4$ deposit to test specimens, stress-rupture tests using the coated specimens were carried out. Shown in Table 7 are comparative stress-rupture properties of stainless alloy 310 tested under four conditions: a reference test in pure N_2, the test results obtained in Phase 1 using synthetic combustion gas, a third test representing the procedures



310
66% Elongation
Stress 110 MPa

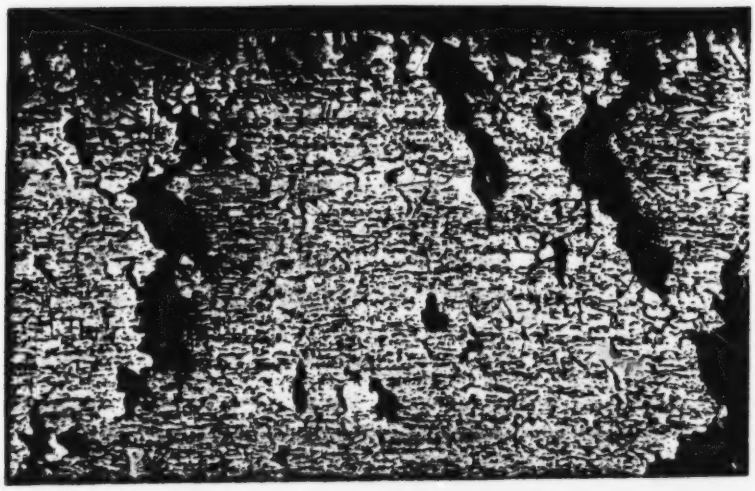


347H
34% Elongation
Stress 159 MPa

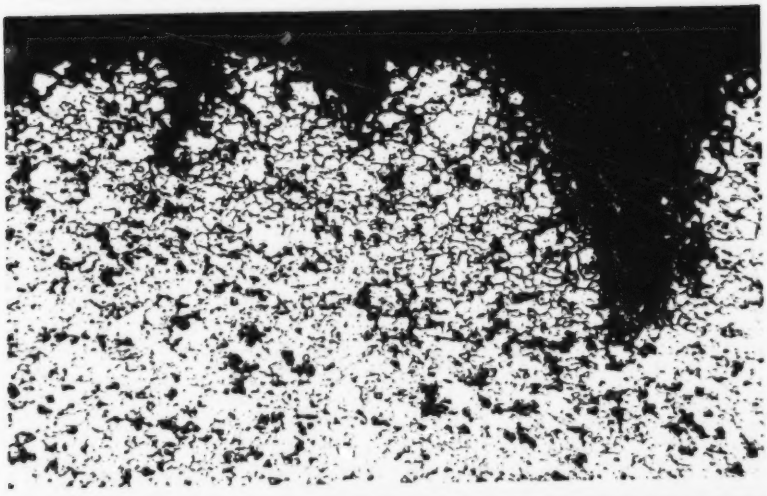


HK40
12% Elongation
Stress 131 MPa

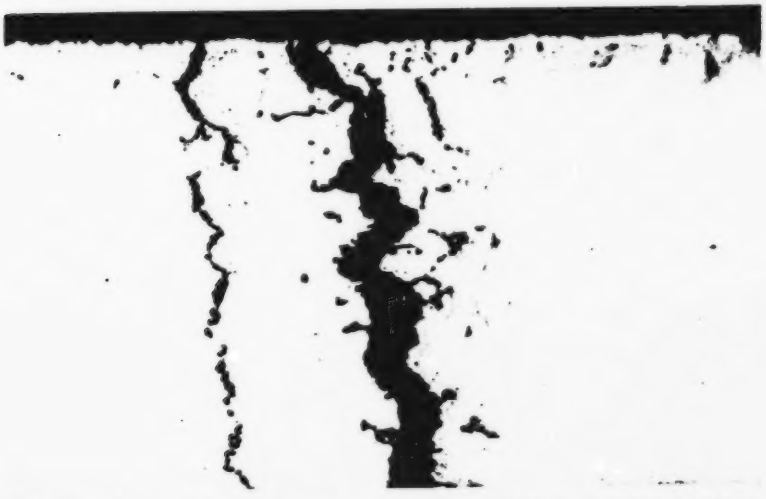
Figure 20 Photomicrographs Showing Examples of Surface Attack in 310, 347H and HK40 When Tested at 800°C Using a High Stress in Synthetic Combustion Gas (X100)



310
Stress 20.7 MPa
Life 834 h
900°C



347H
Stress 14.5 MPa
Life 641 h
900°C



HK40
Stress 31.7 MPa
Life 957 h
900°C

Figure 21 Photomicrographs of 310, HK40 and 347H After Testing Using a Low Stress in Synthetic Combustion Gas

Table 7 Comparative Stress-Rupture Data* on Stainless Alloy 310

Description	Atmosphere (Type)	Deposit	Time to Rupture (h)	Elongation (%)
Reference	N_2	None	64.7	40
Phase 1	Synthetic Combustion	None	50.2	37
Phase 2	Synthetic Combustion	Loosely Packed	102.7	27
Phase 2	24 h Synthetic Combustion 24 h Argon Bal Synthetic Combustion	Loosely Packed	67.5	33

* All tests conducted at 900°C and 34.5 MPa

proposed for Phase 2 using the deposit and synthetic combustion gas and a fourth test which was similar to test three except that pure argon was substituted for synthetic combustion gas for a 24 h period during the test. This latter test was conducted to test the hypothesis that at 900°C a protective oxide coating was being formed which prevented catastrophic corrosive attack by the deposit.

These data show that rupture life was longest for the coated specimen tested in synthetic combustion gas followed by the coated specimen in argon interrupted synthetic combustion gas. Shortest time was apparent for the uncoated specimen tested in synthetic combustion gas. Although these data suggest that the formation of a protective oxide coating and use of the simulated deposit appeared to be protecting the specimen, some evidence of severe corrosion was apparent in isolated areas of a few of the coated specimens. Figure 22 for example shows a cross section of a blister which had formed on a coated 310 specimen and illustrates severe sulphidation. However at the stress level used for these tests, it appeared that mechanical failure occurred before hot corrosion could affect rupture life. It will be interesting to learn during Phase 2 stress-rupture testing if the use of coated specimens will adversely affect the rupture life of the alloys at lower stresses.

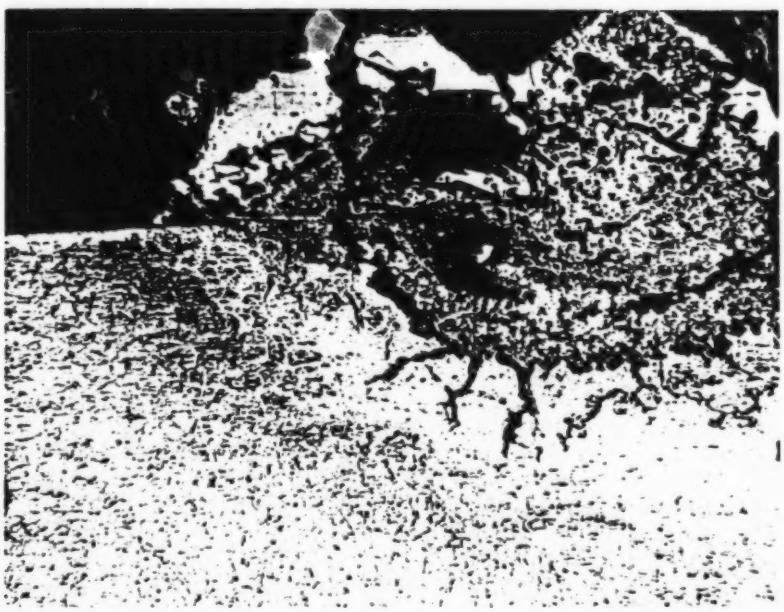


Figure 22 Photomicrograph Showing Cross Section of a Blister on Simulated Deposit Coated Alloy 310 After Testing in Synthetic Combustion Gas (X100)

POOR

QUALITY

ORIGINAL